ELSEVIER

Int. J. Production Economics 40 (1995) 219–230

international journal of
production economics

Layout problem for an aircraft maintenance company tool room

Lee Miu-ling Rosa, Bruce R. Feiring*

Department of Applied Statistics and Operational Research, City Polytechnic of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong

Received on 15 October 1993; accepted for publication 7 September 1994

Abstract

A tool room of an aircraft maintainance company with 10 000 tools is considered. These tools are borrowed by the mechanics when needed and must be returned before the end of shift. About 400 in–out transactions are handled by the storekeepers of the room. However, since the room is usually crowded with mechanics at their shift start/end times, the storekeepers are overloaded and significant productive manpower is held up in waiting for the tools. Therefore, the racks and tools in the tool room are required to be rearranged so that the handling time of the in/out transactions can be reduced.

The racks are rearranged by heuristics and then tools are allocated to the racks according to request probabilities, which are estimated by the proportion of each tool's on-loan frequency to the total on-load frequency during December 1992. Effectiveness is measured by comparing the total rectilinear distance travelled to fetch the tools requested during 11–15 January 1993 based on the proposed changes, to that based on existing rack and tool arrangement. It was found that improvement by tool allocation according to the request probabilities could reach up to 39% with the existing rack arrangement. Furthermore, minor rearrangement on the racks could also reduce the distance travelled by 12%.

Keywords: Aircraft maintainance; Tool room; Layout problem

1. Introduction

1.1. Layout design

Layout is the spatial arrangement of physical resources within an area. Layout design is the process to devise a good, workable and effective arrangement of the resources of a unit. Effectiveness of a layout design is measured by the costs of the interactions/work flows among the resources. The problem in layout design is how to achieve the relative placement/assignment of different resources to different locations within an area, so that the total cost of interactions is minimal. The most widely addressed real-world problems are the office and plant layout problem.

1.2. Tool room and its operations

Aircraft maintenance industry is technical labour intensive. Tooling is one of the supporting functions in the industry. Its importance lies on the

* Corresponding author.

SSDI 0925-5273(94)00079-4

availability of suitable equipment to get the job done efficiently. Tooling is provided to the mechanics at two levels. One is that each mechanic has a set of hand tools of his own. Other expensive or special tools will be kept in the tool room and can be borrowed when needed. According to company rules, all the borrowed tools must be returned to the tool room before the shift end time of the mechanic.

A tool room of area 300 m^2 with approximately 10 000 tools is considered. The tool room is assumed to be operated by a total of 12 storekeepers on shift basis round the clock.

The tool in–out transactions are currently handled manually through the "on loan log book". The storekeepers can recall most of the locations of the tools from their memory. For those rarely demanded tools, they can check against the master location index by the tool name.

1.3. Problem analysis

Every day, more than 400 tools will be issued and they are required to be returned on the same day. Although the tool room is open at all times, it is usually overloaded at the shift start time when tools are borrowed and at shift end time when tools are returned. The queue length could be up to 30–40 mechanics. The average number of waiting staff during the peak hours from 08:15 to 08:45 was 5.98, the average waiting time was 4.25 min, the average number of transactions during this period was 60, and therefore, the unproductive manpower held up in the tool room was 4.25 manhours every day just within that 30 min interval. If these figures also apply to the night shift mechanics, there will be a total of 8.5 manhours wasted every day. Furthermore, there may also be staff waiting in the hangar for the tools to start their work. Therefore, the cumulative manhour wastage due to tool hang-up could be very significant.

The loan transaction time can be decomposed into two factors, viz. (1) the fetch time of the tools from racks to service counter and (2) the recording time of the loan details on the "on loan log book". The return transaction time on the other hand, consists of the searching time of the loan details from the "on loan log book" as well as the replacement time of the tool back to the rack.

The recording and searching times of the loan details can be reduced if the tool in/out transaction is computerized or bar-coded. However, since the requirement in manning the tool room is quite tight, there is little likelihood that improving the tool room operation can reduce the headcount. Therefore, computerization costs cannot be justified. Alternatively, rearrangement of the tools is considered in order to reduce the tool retrieval/replacement time.

2. Related literature

Over the past 40 years, many techniques and approaches have been developed to deal with facility layout problems. The review of El-Rayah and Hollier [1] describes various approaches and provides further references.

The traditional schematic techniques introduced before the mid-1950s, include operation process charts, flow diagrams, etc. and the development and evaluation of alternative layout concepts. These techniques depend primarily on the judgement, intuition and experience of the layout analysts. The commonplace mathematical model for process layout concept is the load–distance model.

The problem of assigning n facilities to n locations is treated as a special case of (i) the quadratic assignment problem, and (ii) the travelling salesman problem. The model for the quadratic assignment problem is a model with $n!$ feasible solutions. Hence, determining the optimal solution by complete enumeration is infeasible for problems of interesting size. Although branch-and-bound procedures can substantially reduce the solution space to be evaluated, it still has not been successful in solving real-size problems (i.e. more than 15 departments) in a reasonable amount of time. Computerized heuristic algorithms such as best pairwise exchange heuristic, greatest to least heuristic and many others have been developed to overcome the computational difficulty associated with complete enumeration. These algorithms deal with two basic phases – (1) construction of new layouts and (2) improvement of existing layouts – to generate suboptimal, reasonably acceptable solutions. Some of the well known computerized layout planning routines that have been reported are the computerized relative allocation of facilities technique (CRAFT) [2], the automated layout design program (ALDEP) and the computerized relationship layout planning (CORELAP).

The use of computers in facilities layout requires that the problem be expressed in quantifiable terms, but the nature of the layout problem requires many factors to be taken into account and balanced in the evaluation of layout. Interactive routines introduced in early to mid-1980s overcome this difficulty by allowing interaction between the computer routines and the user during the execution of the program. The integrated approach involves integration of computer software technologies, i.e. decision support system (DSS), computer-aided design (CAD) and management information system (MIS), for the task of integrating the expertise of the human planners with the computational efforts required for the solution of the layout problem.

The multigoal approach was introduced in the early to mid-1980s, which formulates the layout problem as a quadratic assignment problem with the conflicting objectives of minimizing the material handling cost and maximizing a closeness rating measure. Multigoal heuristic algorithms for facility design problems were developed by Dutta and Sahu [3]. The major advantages are that these algorithms do an excellent job of keeping separate those facilities which have undesirable closeness ratings, and the method is very efficient in terms of computational effort.

The graph theoretical approach, introduced in the early to mid-1980s, is applicable when the facility area and shape are less important than adjacency while the load intensities among facilities are location dependent. According to Massan and Hogg [4], an upper bound of the optimal solution is to be established which can serve as a benchmark for evaluating the resulting solutions and as many adjacency relationships as possible must be satisfied in order to improve the quality of the suboptimal solution.

The knowledge-based or expert system approach was introduced in the mid-1980s. It combines the judgement of human experts with quantitative tools in order to develop good facilities layout for a variety of unstructured design situations.

Karwowski and Evans [5] illustrate the potential applications of fuzzy methodologies to various areas of production management. One of the prominent areas identified by the authors was facilities planning which includes such problems as facilities layout design and material handling system design. The approach based on fuzzy sets theory provides a framework for modelling problems which are inherently vague.

Gray, Karmarkar and Seidmann [6] provided references on storage algorithms which can also be employed to solve the layout problem. The earliest dedicated storage algorithm is the cube-per-order index (COI) rule of Heskett [7], where the COI of an item is defined as the ratio of the item's total required space to the number of trips required to satisfy its demand. The algorithm consists of locating the items with the lowest COI closest to the picking/delivery (P/D) point, that is those items which combine a high turnover frequency with a low space requirement. Items are then assigned to locations progressively farther away from the P/D point by increasing COI. Although this algorithm was initially conceived as a heuristic, it yields an optimal solution to the exact mathematical programming formulation of the same problem, assuming a single-command system, single-order picking and that the cost of moving all items is constant and proportional to the distance travelled.

Jarvis and McDowell [8] derived some stock location algorithms for an order picking warehouse having blocks of parallel aisle with cross-overs only at the ends of the aisle. The optimal strategy is to locate products with the highest probability of being included in orders, on shelves nearest to the dock.

Whenever possible, it is desirable to incorporate information about typical order profiles in the derivation of storage policies. Van Oudheusden, Tzen and Ko [9] and Van Oudheusden and Zhu [10] examined a situation occurring in a multi-command automatic storage/retrieving system (AS/RS) rack, where orders are assumed to recur according to a known probability. They derive an optimal solution based on pure sequencing theory for the case of a two-dimensional rack and overlap orders.

3. Assumptions and limitations

- The location and size of the tool room is fixed. Hence, the inter-relationships of the tool room with other departments will not be considered and the service counter of the tool room will not be changed.
- Total number of tools remains unchanged in the foreseeable future.
- Past pattern of tool issue and return will continue over the planning horizon.
- The tool retrieval/replacement time is dominated by the travelling time.
- The tool room is considered as a two-dimensional storage area and hence, the placement of a tool on the top or bottom position will not affect the retrieval/replacement time.
- Travelling speed between the service counter and the racks is constant and equal among all storekeepers.
- Storage/retrieval of the tools is still to be handled manually.
- The storekeepers easily adapt to the new distribution of tools. Hence, there will not be any changes to the tool location identification time.
- The storekeepers only pick and replace one tool at a time, i.e. the tools are not batched.

4. Methodology

4.1. Special considerations about the tool room

(a) Aircraft tools are excluded from the project because they are usually requested by code. In addition, the demand is induced from the aircraft type being maintained. So, past patterns of aircraft tool usage may not be applicable.

(b) Only the general-purpose tool area will be considered. Also, in order not to block the entrances and exits of the tool room, some reserved areas will be defined where racks cannot be placed.

(c) The service counter is a table of 2 m length. Its location is considered to be at the mid-point of the table.

(d) The capacity of a rack is usually measured by its volume. However, the tools are actually placed onto the rack as shown in Fig. 1. That is, there must be empty spaces on top of each tool to allow for picking and replacement motion. The size of this space is not fixed. Provided that the level height of the rack is greater than the height of the container of the tool with allowances for movement, the tool can be placed onto the rack. Since the level height is approximately the same among the racks, instead of using its volume, the effective capacity of a rack is calculated as the product of the number of levels on the rack and the floor area it occupies. Moreover, for safety purposes, the heavy tools are placed only in the lower levels of a rack while the light tools can be placed in either the upper levels or the lower levels. To cope with this requirement, the rack capacity is further divided into three sub-capacities, viz. the light capacity, medium capacity and heavy capacity, according to the number of high levels, medium levels and low levels defined for the rack.

(e) The representative point within a rack is its mid-point. The distance from the service counter to a rack is calculated as a rectilinear distance from the point of service counter $(x1, y1)$ to the mid-point of the rack $(x2, y2)$ which is the sum of $|x2 - x1|$ and $|y2 - y1|$. Often, the path from the

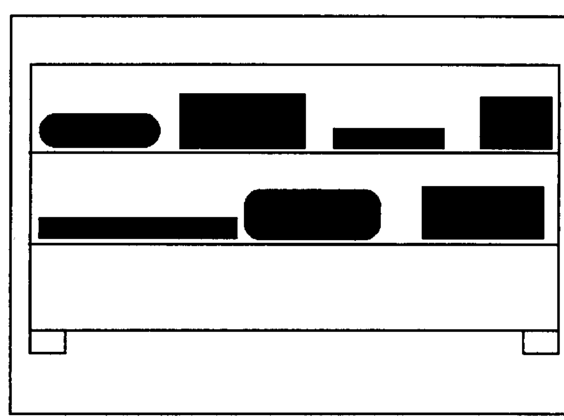

Fig. 1. Tools on rack.

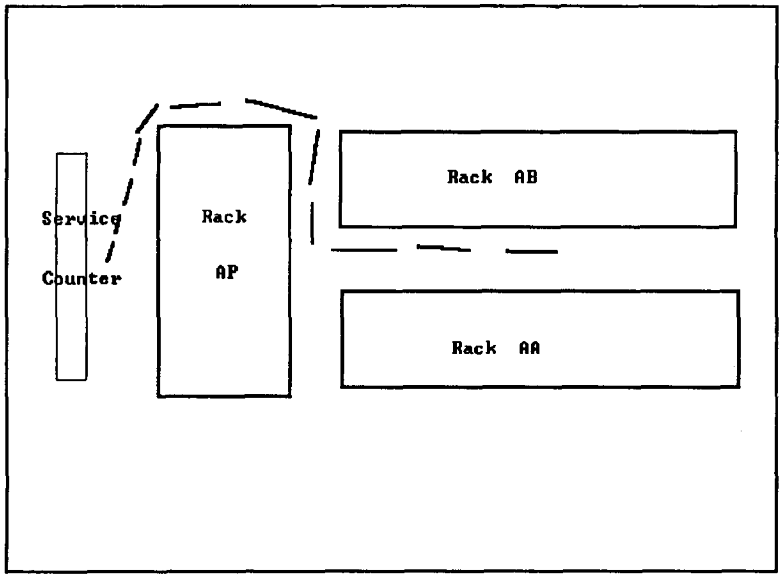

Fig. 2. Tool retrieval/replacement path.

service counter to the rack is wholly blocked by another rack, as shown in Fig. 2.

In this case, the storekeeper cannot go through the rack, so he must go to the aisle of the blocking rack first and then go to the target rack, as indicated by the dashed line. Let the point of the aisle of the blocking rack be ($x3$, $y3$), the distance then becomes

$$|x3 - x1| + |x2 - x3| + |y3 - y1| + |y2 - y3|.$$

(f) Tools of different specifications may be considered as different tools, such as drill of different diameters and hammer steel of different weights. However, if they are considered as different tools, the number of tools to be modelled will be over 2000. Also, it is more practical for the storekeepers to memorize the location of hammer steel, than the location of hammer steel 4 lb. In order to assist the storekeepers to locate the tool from their memory rather than the location log book, tools of the same description but different specifications are grouped together. After this grouping, there are a total of 228 general-purpose tools identified.

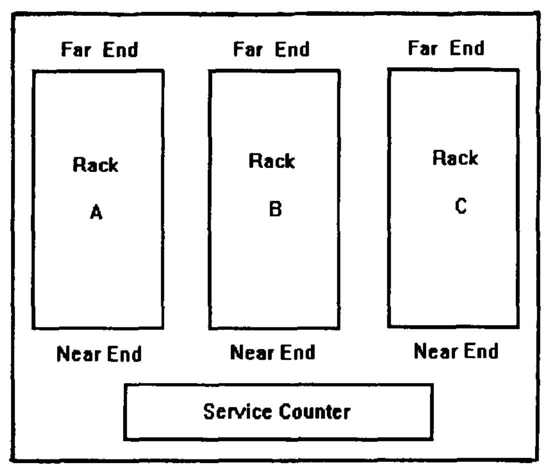

Fig. 3. Rack far/near end.

(g) Refer to Fig. 3, the distance from the service counter to the near end of rack C may be shorter than that from the counter to the far end of rack B. Since, some of the racks are quite long, this difference can be as long as 3–4 m. Therefore, the distance of a tool cannot be approximated by the rack distance. To simplify the case, the rack is divided into three partitions – near, middle and far. The tool distance is calculated as the distance from the service counter to the mid-point of the partition where the tool is placed. If a tool is placed across two partitions, say, middle and far, the shorter distance will be assumed, i.e. the distance to the middle partition.

(h) Tools stored in rack AV and AW are for handling oils and lubricants. Therefore, they must be stored in the "oil room" where rack AV and AW are located, otherwise, they would contaminate other tools. On the other hand, rack AV and AW are not for storing tools other than oily tools. Hence, the tools currently stored in rack AV and AW will not be allocated to other racks and the location of the racks AV and AW will be excluded from the rearrangement.

4.2. *Model formulation*

The following notations are used:

- m no. of racks
- n no. of tools
- Ω set of possible layouts under the given conditions
- d_{Γ_i} distance of the tool i from service counter while $\Gamma \varepsilon \Omega$ is the implemented layout
- f_i request frequency of tool i

The layout Γ is required to be devised so that the overall retrieval distance is minimized, i.e.

$$\min \sum_{i=1}^{n} f_i d_{\Gamma_i}.$$

Firstly, the racks have to be arranged within the tool room. Three rack arrangements are proposed:

(1) *Revised rack arrangement 1*: Since the rack AP is blocking the path from the service counter to the racks AA and AB, the racks are rearranged with the following changes:

- rack AP changed from horizontal orientation to vertical orientation;
- rack AA moved down;
- rack AB moved up;
- rack AM and BB changed from horizontal orientation to vertical orientation;
- as space is available, rack AR is moved to below AA.

The proposed layout will be as shown in Fig. 4.

(2) *Revised rack arrangement 2:* Based on the rack rearrangement layout 1, the racks are rearranged further to have a better outlook as in Fig. 5.

(3) *New rack arrangement*: The following procedure is used to derive a totally different arrangement of the racks in the tool room:

- Sequence the racks, except AV, AW, AX, AY, into an ascending sequence of rack length.
- Start from the first rack in the sequence, find a point nearest to the service counter but leaving 50 cm for a pathway. The selection of the point should take into consideration reserved areas defined in the tool room. Put the rack vertically with the left vertex at the point found.
- Continue with the other racks in the sequence so that the distance from service counter to the rack is the shortest and the racks are separated by at least 50 cm.

This rack arrangement logic is coded and the output layout as in Fig. 6 is found.

After deciding on the position of each rack in the tool room, the tools are allocated to the racks. Tool allocation can be found by the following integer linear programming (ILP) model:

$$\min \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{3} f_i d_{jk} X_{ijk},$$

where d_{jk} is the distance from the service counter to the centre of partition k of rack j, and X_{ijk} is 1 if tool i is placed into the partition k of rack j and 0 otherwise. However, the definition of the partition of a rack in ILP model is so rigid that a tool cannot be placed across two partitions. Also, the build-up of the model is too clumsy to be solved efficiently.

Since most of the tool requests contain one tool only, according to sequencing theory, an optimal solution can be obtained by sequencing the tools according to

$$p[1] \geqslant p[2] \geqslant p[3] \geqslant \cdots \geqslant p[n],$$

where p is the request probability of a tool. The brackets indicate the position in the sequence. Thus $[4] = 3$ means that the 4th tool in the sequence is

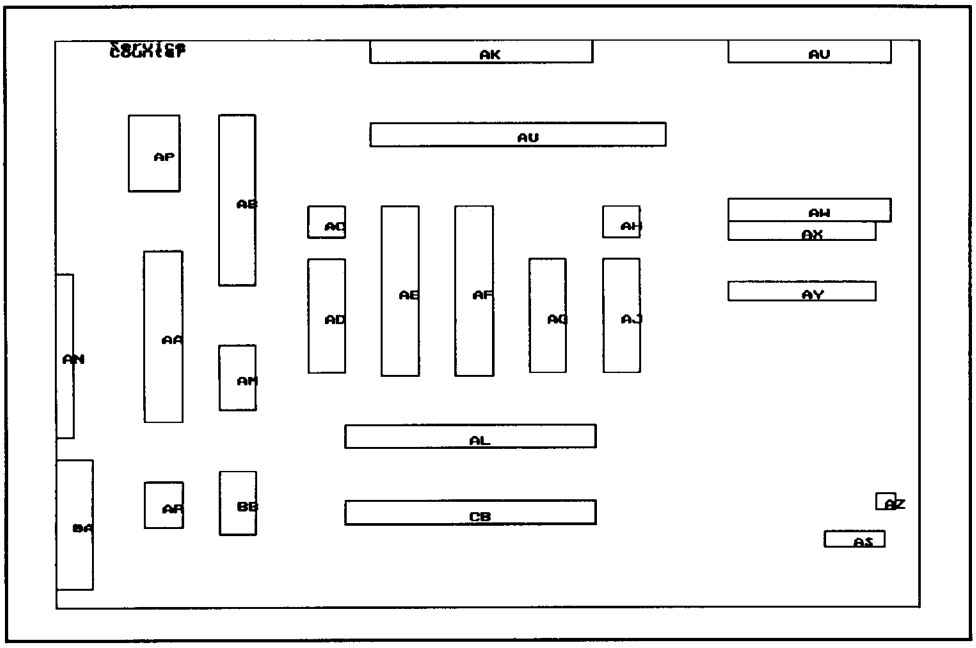

Fig. 4. Revised layout 1.

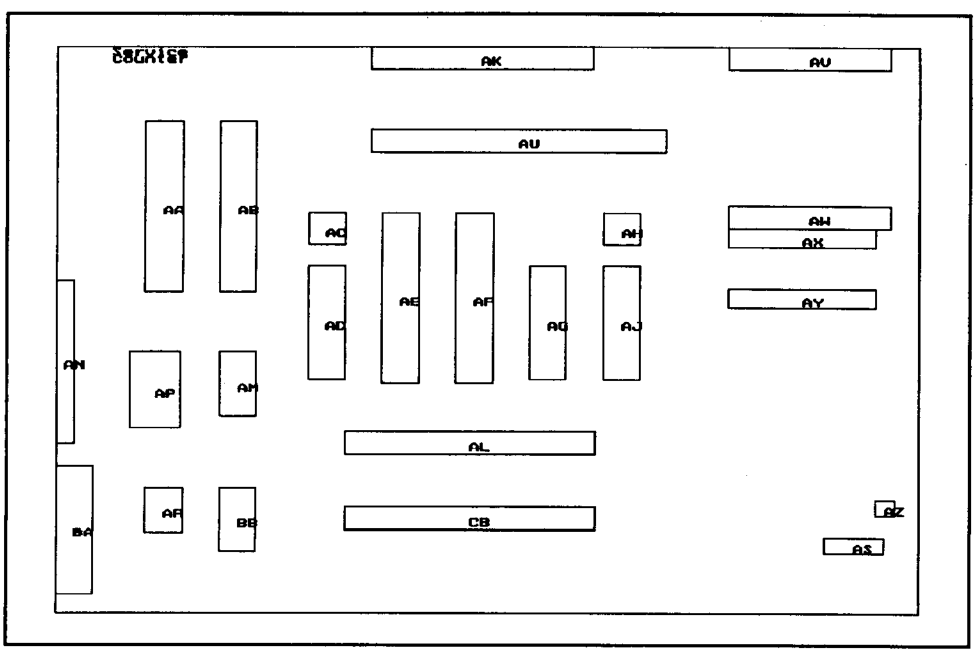

Fig. 5. Revised layout 2.

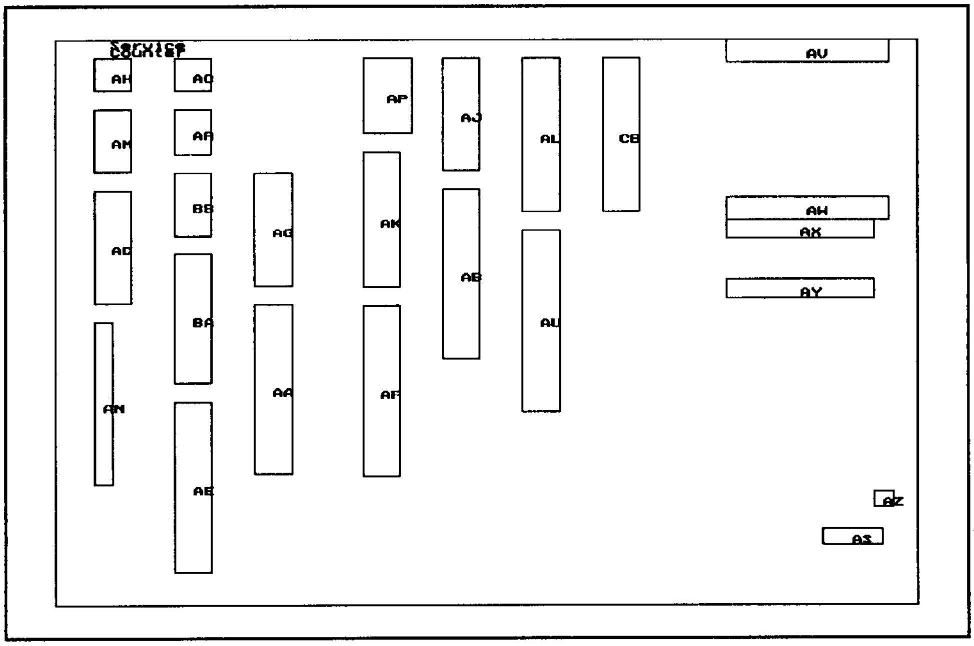

Fig. 6. New rack arrangement.

tool 3. The tool of position [1] is located in the available rack level and partition nearest to the service counter, then the tool of position [2] and so on. If two tools have the same request probability, the tie is broken by selecting the one that requires less floor area. The selection of an available rack level and partition takes into consideration the weight level of the tool as well as the floor area it occupies.

The advantage of this logic is that the rack is only logically partitioned. It is only at the time of calculating the distance of the selected available position, that the partition will be considered. Also, the allocation result can be obtained very quickly. In order to develop the above layouts, data must be collected to estimate the distance of the racks from the service counter and to access the request probabilities of the tools.

4.3. Data collection and aggregation

Four categories of data are required. First is the present layout of the tool room; second is the dimensions of the racks; third is the dimensions of the tools and their current distributions in the tool room; and last but not the least is the loan details which are used for the analysis of the loan profiles of the tools as well as for the estimation of the tool turnover rates.

(1) *Present layout*: The service counter is situated at the top left side. Each rack is represented by a rectangular box marked with a rack name, say "AK", "AA", "AP". The location of each rack in the room is represented by the X–Y coordinates of its top left corner – measured from the layout with origin (0, 0) at the top left vertex of the room and scaled to the actual size – as well as its orientation "V" for vertical and "H" for horizontal.
For example,

Rack	Coordinate from the map	Scaled coordinate	Orientation
AP	(1.0, 0.9)	(120, 180)	H
AK	(4.25, 0.0)	(510, 0)	H
AN	(0.0, 3.1)	(0, 620)	V

Location of the service counter is measured by the scaled x–y coordinates of its centre from the origin, which is (180, 0).

(2) *Rack dimensions, tool dimensions and distribution*: The storekeepers are requested to fill in the storage record form, the details about the rack and the tools together. The rack details collected, together with its location measured, are stored in the data file for analysis.

Currently, there may occur several locations for the same tool, such as crimping tool found in rack AA, AB, AC and AD; soldering iron found in rack AC and AD; air hose found in AF and AP; allen key found in AA, AC and AD, etc. Since this is an undesirable way to handle the tools, these tools are aggregated.

(3) *Loan details*: In order to obtain the loan details, the "on loan log books" were borrowed from the tool room. The details in December 1992 will be analyzed and used for the assessment of the turnover pattern of the tool. The request probability of a tool is estimated by the proportion of the tool's on-loan frequency to the total on-loan frequency in December 1992.

4.4. Data analysis

(1) *ABC analysis on the on*-loan tools: Out of the 228 tools, only 10 of them are frequently borrowed and they cover nearly 60% of all the tool requests. These tools are listed in the descending sequence of their request probabilities as shown in Table 1. As compared to the locations of the racks, it can be found that none of these tools are in the proximity of the service counter.

(2) *Order pattern*: Since a mechanic may borrow more than 1 tool at a time, to verify the no-tool-batching assumption, the probability of each order and the frequencies of different order sizes are calculated.

The order size ranges from 1 to 7, with the distribution shown in Fig. 7. Since over 70% are one-tool requests, the no-batching assumption can be accepted.

(3) *Related tools*: Although less than 30% of the orders contain more than one tool, it can be found that some of the tools are usually borrowed together. As described by the storekeepers, these tools are functionally related.

- Crimping tool with wire stripper (5.5%) and sometimes with removal tool as well (2%);
- Air polisher with air hose (3.6%);

Table 1

Tool	Rack	Level	Pos	Probability
Crimping tool	AB	H	M	0.093
Hand lamp	AH	L	F	0.086
Wire stripper	AD	H	M	0.080
Air hose	AF	L	F	0.078
Ladder	AU	M	M	0.060
Removal tool	AB	H	F	0.056
DM meter	AA	M	M	0.053
AVO meter	AA	M	M	0.039
Air polisher	AR	H	F	0.026
F/T lamp	AR	M	M	0.021
				0.591

4.5. Layout evaluation

Since it is assumed that the tool retrieval/replacement time is dominant by the travelling time from service counter to tool location (which is directly proportional to the travelling distance), to measure the effectiveness of the proposed layouts, the total distances travelled for the on-loan transactions of the days 11–15 January 1993 are to be calculated based on the proposed layouts and compared with that based on the current layout.

There are 2041 on-loan tools and the tools of highest frequency are listed below:

Frequency of the 5 highly requested tools

Tool	Frequency
Air hose	179
Ladder	98
Tap	67
Bit	64
Tap holder	61

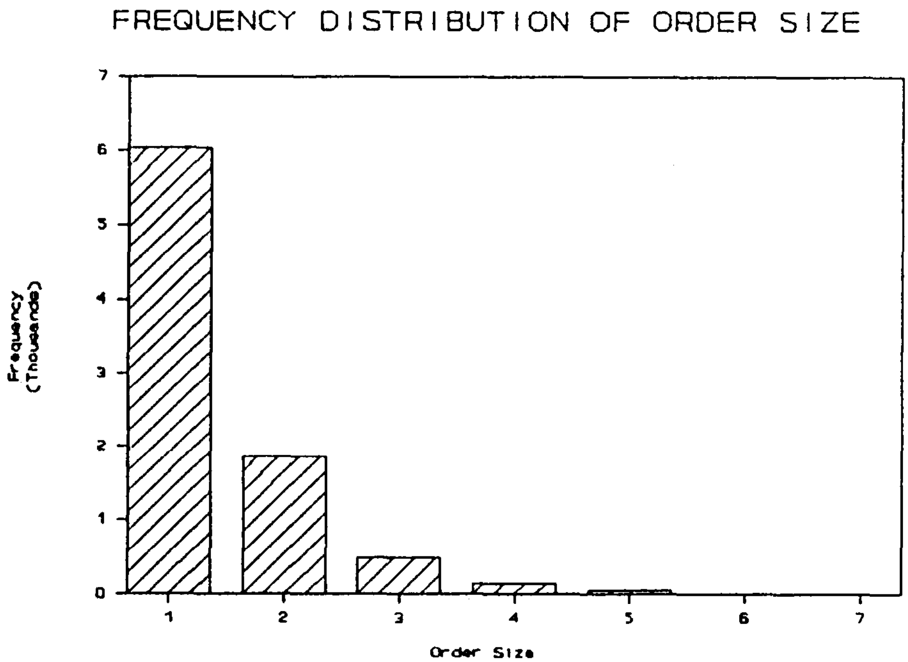

Fig. 7. Order size frequency table.

5. Result interpretation

5.1. Layout comparison

The total distances travelled in meters as well as the saving percentage (enclosed in bracket) are summarized in Table 2.

It is obvious that the new rack arrangement with the proposed tool allocation will result in the greatest saving. If half of the mechanic's waiting time outside the tool room is contributed to the tool retrieval/returning time, this re-arrangement can save one-quarter of the waiting time. That is, one minute can be saved per person. Just considering the 60 transactions handled during peak hour from 08:00 to 08:45, an hour can be saved per day. However, this is the most expensive way because it requires all the racks and tools involved to be moved.

If the tools are allocated to the racks according to the proposed rule, the results from both revised layouts of the existing racks are approximately the same. Actually, the tool allocation rule is so effective that the saving, even with the existing rack arrangement is 39% – very significant.

More than 10% of the travelling distance can be saved from just some minor rearrangement on the racks as in the revised layouts. This is because the

Table 2
Comparison on the total distance travelled with different rack arrangement and tool allocation

Rack arrangement	Existing tool allocation	Proposed tool allocation
Existing	7386.86	4485.64 (39.28%)
Revised layout 1 (Fig. 4)	6806.91 (7.85%)	4211.63 (42.98%)
Revised layout 2 (Fig. 5)	6493.83 (12.09%)	4216.61 (42.92%)
New rack arrangement (Fig. 6)	N.A.	3529.57 (52.22%)

Table 3
Locations of the highly requested tools

Tool	Existing			Proposed		
	Rack	Level	Pos	Rack	Level	Pos
Crimping tool	AB	H	M	AU	H	N
Hand lamp	AH	L	F	AP	L	N
Wire stripper	AD	H	M	AP	H	N
Air hose	AF	L	F	AP	L	N
Ladder	AU	M	M	AP	M	N
Removal tool	AB	H	F	AP	M	N
DM meter	AA	M	M	AP	M	M
AVO meter	AA	M	M	AP	M	M
Air polisher	AR	H	F	AP	H	M
F/T lamp	AR	M	M	AP	M	F

Table 4
Locations of related tools

Related tool	Existing			Proposed		
	Rack	Level	Pos	Rack	Level	Pos
Crimping tool	AB	H	M	AU	H	N
Wire stripper	AD	H	M	AP	H	N
Removal tool	AB	H	F	AP	M	N
Air hose	AF	L	F	AP	L	N
Air polisher	AR	H	F	AP	H	M

storekeepers can directly reach the tools stored in the rack AA, AB, AM and BB, including the highly requested tools. Also, the rack AR is placed nearer to the service counter.

5.2. *Highlights of the changes*

The locations of the highly requested tools based on the proposed allocation rule on the existing rack arrangements are compared with the existing locations (Table 3). Except for the crimping tool, all highly requested tools are put into the rack AP nearest to the service counter. The crimping tool which is too large to wholly fit into rack AP, is put into the larger rack AU, which is just on the right-hand side of the service counter. Although the tool allocation rule does not take tool-batching into consideration, there are also improvements for the retrieval/replacement of the related tools (Table 4).

The related tools are originally placed on different racks and most of them are in the far end of the rack. The allocation rule tries to place them in the near end of the rack.

With rack rearrangement, the allocation of the tools will be totally different from the existing layout. However, the above characteristics remain.

6. Recommendations

6.1. *Periodic analysis on tool borrowing*

The on-loan log book is now currently used for keeping track of tools. However, it contains the useful information about how frequently a tool is being borrowed as well as the profile of the borrowing. Therefore, ABC analysis should be carried out periodically on the log book so as to derive the trend on the tool borrowing as well as to arrange the tools accordingly.

6.2. *Tool allocation*

Currently, the same tool may be placed on different racks far away from each other. Although not necessarily in the same rack, tools of the same kind but different sizes, weights, etc., should be put near to each other so as to aid the storekeepers' memory.

The allocation of tools according to the probability of request is very efficient. In practice, the actual tool request probabilities do not need to be estimated. Just identifying the several highly requested tools and placing them nearest to the service counter can save a lot of storekeepers' time in retrieving/replacing the tools.

6.3. *Rack arrangement*

Efficient placement of the racks is the basis for the layout design of the tool room. A uniform layout allows the storekeepers to reach each rack directly, which in turn saves the time in retrieving/replacing the tools. Therefore, if the movement of all the racks according to the new arrangement is too expensive, the revised layout 2 is highly recommended because it eliminates the blocking of the service counter by the rack AP.

6.4. Further study

(1) *Use of the computer in tool issue and return*: When issuing a tool, the storekeeper will have to fill in the tool details in the log book. When a tool is returned, the log book is searched to identify the corresponding loan details. This is actually very time-consuming and inefficient. Also, the details on the log book are difficult to analyze. This operation can be expedited if a computer device is employed to read the staff badge and record the tool by reading bar codes attached to it, rather than the writing and signing. Such automation not only shortens the time spent in tool issue and return, but can also be extended to some analysis work, such as the identification of overdue tools. This also can generate efficiency reports on employees.

(2) *Location of the service counter*: Currently, the service counter is located in the corner of the tool room. If the service counter can be moved to the centre position, the distance from the service counter to every corner of the room is shortened. In other words, the proximity of the counter is enlarged and hence, the total distance from the counter to every rack is shortened.

References

[1] El-Rayah, T.E. and Hollier, R.H., 1970. A review of plant design techniques. Int. J. Prod. Res., 8: 263–279.

[2] Buffa, E.S. and Armour, G.C., 1991 and Vollmann, T.E., 1964. Allocating facilities with CRAFT. Har. Bus. Rev., 42: 136–159.

[3] Dutta, K.N. and Sahu, S., 1982. A multigoal heuristic for facilities design problems: MUGHAL. Int. J. Prod. Res., 20: 147–154.

[4] Massan, M.M. and Hogg, G.L., 1991. On constructing a block layout by graph theory. Int. J. Prod. Res., 29: 1263–1277.

[5] Karwowski and Evans (1986)

[6] Gray, A.E., Karmarkar, U.S. and Seidmann, A., 1992. Design and operation of an order-consolidation warehouse: Models and application. Eur. J. Oper. Res., 58: 14–36.

[7] Heskett (1963)

[8] Jarvis, J.M. and McDowell, E.D., 1991. Optimal product layout in an order picking warehousing. IIE transaction 23(1): 93–102.

[9] Van Oudheusden Tzen and Ko (1988).

[10] Van Oudheusden, D.L. and Zhu, W., 1992. Storage layout of AS/RS racks based on recurrent orders. Eur. J. Oper. Res., 58(1): 48–56.

[11] Raoot, A.D. and Rakshit, A., 1991. A fuzzy approach to facilities layout planning. Int. J. Prod. Res., 29: 835–855.

[12] Foulds, L.R. and Robinson, D.F., 1978. Graph theoretic heuristics for the plant layout problem. Int. J. Prod. Res., 16: 27–37.

[13] Cormier, G. and Gunn, E.A., 1992. A review of warehouse models. Eur. J. Oper. Res., 58: 3–13.

[14] Bozer, Y.A. and White, J.A., 1984. Travel-time models for automated storage/retrieval systems. IIE transactions, 16: 329–338.

[15] Hausman, W.H., Schwarz, L.B. and Graves, S.C., 1976. Optimal storage assignment in automatic warehousing systems. Management Science, 22(6): 629–638.

[16] Park, Y.H. and Webster, D.B., 1989. Modelling of three-dimensional warehouse systems. Int. J. Prod. Res., 27(6): 985–1003.

[17] Ritzman, L., Bradford, J. and Jacobs, R., 1979. A multiple objective approach to space planning for academic facilities. Management Science, 25(9): 895–906.

[18] Foulds, L.R. and Tran, H.V., 1986. Library layout via graph theory. Comput. Indust. Eng., 10: 245–252.

[19] Seppanen, J.J. and Moore, J.M., 1970. Facilities planning with graph theory. Management Science, 17: B242–253.

[20] Svestka, J.A., 1989. Interactive and graphic implementations of the dedicated storage warehouse design model. Comput. Indust. Eng., 17: 49–54.

[21] Scriabin, M. and Vergin, R.C., 1975. Comparison of computer algorithms and visual based methods for plant layout. Management Science, 22: 172–181.

[22] Baker, K.R., 1974. Introduction to Sequencing and Scheduling. Wiley, New York.

[23] Everett, E.A., Jr, and Ronald, J.E., Production and Operations Management: Concept, Models and Behaviour. 4th ed. Prentice-Hall, Englewood Cliffs, NJ.